Available online at www.sciencedirect.com

SCIENCE DIRECT

ELSEVIER

Physica C 435 (2006) 12–15

PHYSICA C

www.elsevier.com/locate/physc

The mechanisms responsible for broadening of the resistive transition under magnetic field in the Josephson junction network realized in bulk YBCO + CuO composites

D.A. Balaev *, S.I. Popkov, K.A. Shaihutdinov, M.I. Petrov

Kirensky Institute of Physics, 660036 Krasnoyarsk, Russia

Abstract

The experimental results of the effect of the magnetic field (up to 60 kOe) on the broadening of the resistive transition of bulk composites $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ (YBCO) + CuO are presented. These composites represent the network of the tunnel-type Josephson junctions where the copper oxide acts as a material forming barriers between YBCO crystallites. The mechanisms responsible for broadening of the resistive transition under magnetic field are discussed. The analysis of experimental $R(T)$ dependences have shown that in the low field range 0–10^2 Oe, the $R(T)$ dependences are described well by the Ambegaokar–Halperin (AH) model. In the range 10^3–6×10^4 Oe, the dissipation follows Arrhenius law $R \sim \exp(-U(H)/k_BT)$ characteristic for thermally activated flux creep model. In the range $H \sim 10^2$–10^3, the crossover from AH to flux creep dissipation mechanisms occurs.

PACS: 74.50.+r; 74.60; 74.80.Bj

Keywords: Josephson network; YBCO + CuO composites; Dissipation; Magnetic field

1. Introduction

In our previous work [1], the results of the study of magneto-resistive (MR) effect in bulk composites YBCO + CuO have been presented. The composites exhibit a very high sensitivity of resistivity to weak magnetic fields. The broadening of resistive transition of the composites under the influence of weak magnetic fields (less than 200 Oe) is observed for a wide temperature range ~50–90 K [1] in contrast to "pure" polycrystalline HTSCs where this temperature interval is very narrow, typically amounting to several degrees (85–90 K for the yttrium HTSC [2]). This effect has been pointed to be attractive for practical applications [1]. The composite HTSC materials demonstrating such a giant MR effect can be used as active elements in magnetic field sensor devices. In this report, we discuss the physical mechanisms responsible for the broadening of the resistive transition $R(T)$ of the composites HTSC + CuO under magnetic field. Two classical models: the flux creep model [3] related to the Josephson media and the Ambegaokar–Halperin (AH) model [4] of phase slip in Josephson junctions are used for the interpretation of the experimental data.

2. Experimental

Composite samples with 70–85 vol.% of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ (YBCO) and 30–15 vol.% CuO have been prepared by the fast baking technique described in [1]. Hereafter, we denote composite samples as YBCO + *V*CuO, where *V* is volume content of CuO; the volume content of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ is 100 − *V*. The $R(T)$ dependences have been measured by standard four-probe technique.

---

* Corresponding author. Fax: +7 3912 438923.
E-mail address: smp@iph.krasn.ru (D.A. Balaev).

0921-4534/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2006.01.008

The samples have been cooled in zero magnetic field (the Earth magnetic field has not been screened). The transport current was perpendicular to the magnetic field direction.

3. Results and discussion

In Ref. [5], it was shown that in the composites YBCO + CuO prepared by the fast backing technique, CuO forms barriers separating the YBCO crystallites and these composites represent a network of Josephson junctions. Figs. 1 and 2 show $R(T)$ dependences of composites YBCO + 15CuO and YBCO + 30CuO measured in various magnetic fields. The resistive transition of composites is characterized by two distinctive sections, a steep part associated with the onset of superconductivity in YBCO crystallites and a broad foot structure coming from the transition of network of Josephson junctions. Such a behavior is a remarkable feature of granular superconductors [5–9]. Weak magnetic fields (less than ~500 Oe) mainly affect the second part of resistive transition, which result in large MR effect at a certain temperature (for example, at 77 K). Let us consider processes in a random network of Josephson junctions under the influence of magnetic field.

Tinkham and Lobb [10] have argued that Ambegaokar–Halperin (AH) model [4] of phase slip in Josephson junctions can be applied for granular superconductors because the periodic potential considered in AH model [4] is a good mathematical equivalent of pinning sites in a network of Josephson junctions. Jumps of flux vortices from site to site lead to slip of the phase of superconducting order parameter on 2π which results in dissipation. According to [4], in the limit of very small transport current, the $R(T)$ dependence at $T < T_C$ defines as

$$R = \{I_0(\hbar I_C(T)/2ek_BT)\}^{-2} = \{I_0(E_J(T)/2k_BT)\}^{-2}, \qquad (1)$$

where $\hbar$, and k_B are Plank and Boltzmann constants, e is the electron charge, I_0 is the modified Bessel function, $I_C(T)$ is a maximum Josephson current at temperature T in the absence of noise, E_J is the Josephson coupling energy depending on temperature and magnetic field

$$E_J(T,H) = \hbar I_C(T,H)/e. \qquad (2)$$

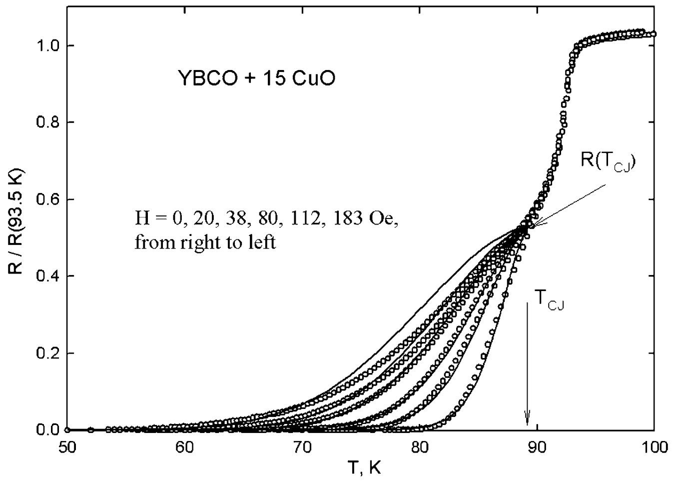

Fig. 1. Experimental dependences of resistance of YBCO + 15CuO composite-circles. Solid curves are the best fits by AH model—Eq. (1) with $E_J = 260$, 170, 130, 100, 85, 70 meV for $H = 0$, 20, 38, 80, 112, 180 Oe, respectively.

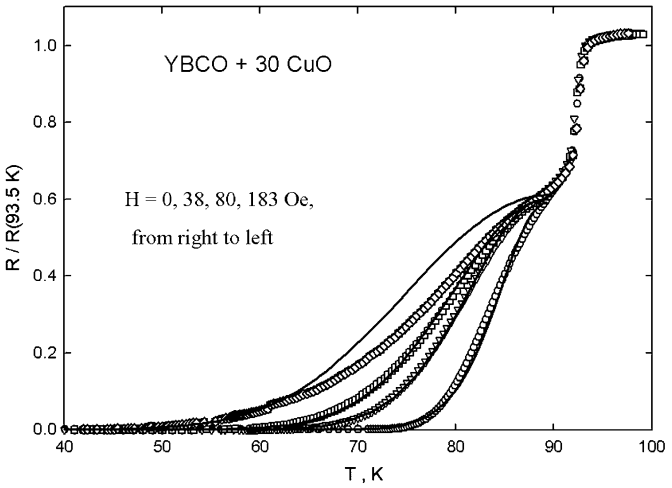

Fig. 2. Experimental dependences of resistance of YBCO + 30CuO composite-circles. Solid curves are the best fits by AH model—Eq. (1) with $E_J = 150$, 95, 70, 52 meV for $H = 0$, 38, 80, 180 Oe, respectively.

The $E_J(T,H)$ related for network of Josephson junctions is averaged or effective Josephson coupling energy [7]. The temperature and magnetic field dependence of E_J for granular superconductor is determined by critical current of Josephson junction network. Calculation of the Eq. (1) allows to reproduce the shape of broad foot structure of experimentally observed resistive transition of granular superconductors. Several authors interpreted $R(T)$ curves (namely, the smooth part of resistive transition) of polycrystalline HTSC [6,7] and HTSC based composites [5,8] using AH model. Phenomenological temperature dependence of the critical current has been proposed as $(1 - T/T_{CJ})^n$ [6–8], where n is fitting parameter, depending on magnetic field. So far as tunnel-like type Josephson junctions realize in the composites under study, we use classical Ambegaokar–Baratoff (AB) [11] theoretical temperature dependence of critical current as $I_C(T)$. This dependence determines temperature behavior of E_J. Thus, besides $I_C(T)$ and two invariable parameters: the resistance in the normal state $R(T_{CJ})$ and the critical temperature of Josephson junction network T_{CJ}, pictured in Fig. 1, there is only one fitting parameter in Eq. (1)—the value of E_J. Figs. 1 and 2 show the results of the best fit of $R(T)$ for composites YBCO + 15CuO and YBCO + 30CuO, respectively. There is a good agreement in the whole temperature range between experimental and theoretical curves for magnetic fields up to ~10^2 Oe. The tails of $R(T)$ dependences measured at magnetic fields more than ~10^2 Oe cannot be satisfactorily described by Eq. (1).

In the flux creep model [3], the resistance caused by motion of vortices is given by Arrhenius relation

$$R = R_0 \exp(-U(H,T)/k_BT), \qquad (3)$$

where R_0 is preexponential factor, $U(H,T)$ is the activation energy. In case of polycrystalline or composite HTSCs, $U(H,T)$ is temperature and field dependence of effective pinning potential in the intergrain media. In some cases temperature independent behavior of U is observed [12,13]. Fig. 3 shows Arrhenius plots of resistive transition for composite YBCO + 30CuO. It is seen from Fig. 3a that $R(T)$ dependences measured in weak magnetic fields (less than $\sim 10^3$ Oe) cannot be described by Eq. (3) with temperature independent $U(T)$. From the other hand, the dependences $\log R$ vs $1/T$ measured at magnetic fields 1, 10 and 60 kOe are straight lines in a wide temperature range, see Fig. 3b, which point out applicability of Eq. (3) with temperature independent $U(T)$. We have examined experimental $R(T)$ curves measured in weak magnetic fields using phenomenological dependence of $U(T) \sim (1 - T/T_{CJ})^n$ in (3). The agreement of experimental and theoretical curves was worse than that for AH model, see Figs. 1 and 2. Similar behavior is observed for sample S + 15CuO (not shown).

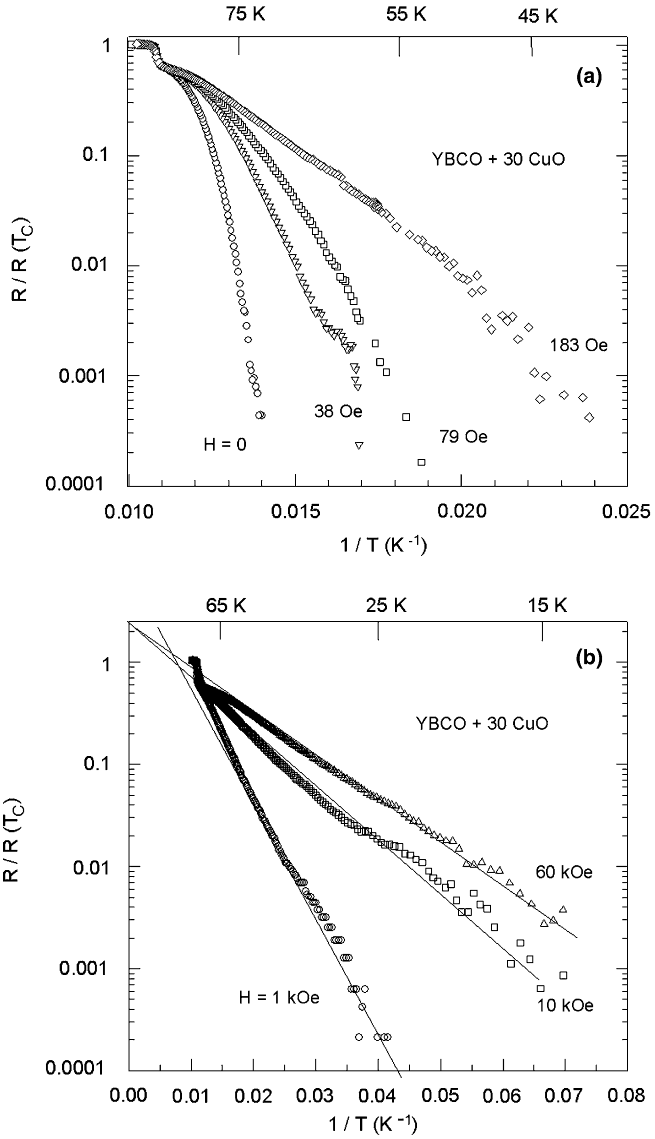

Fig. 3. Arrhenius plots of $R(T)$ for YBCO + 30CuO composite at various H.

Thus, the resistive tails of composites are successfully described by AH model in the low magnetic field range and by flux creep model in the high magnetic field range. As it was pointed out in Ref. [14], in the flux creep model, the physical picture differs from the AH model only in the choice of the pinning potential. In the AH model the potential is periodic, whereas in the flux creep model there is no stipulation that the pinning sites have any relation to each other. With increase of the magnetic field, the influence of the Lorentz force results in change of the profile of coordinate function of pinning potential with decrease of the pinning force. Only the most deep pinning sites remain in the high magnetic fields, i.e., in the high magnetic field range, the coordinate function of pinning potential becomes close to that for flux creep model. In the range 10^2–10^3 Oe, the coexistence of both AH and flux creep mechanisms or the crossover from AH to flux creep behavior takes place.

In Fig. 4, we plotted the values of $E_J(T = 0, H)$ obtained from the best fit of $R(T)$ by AH model and $U(H)$ derived from the slopes of Arrhenius plots of experimental $R(T)$. The $E_J(H)$ and $U(H)$ dependences are seen to have the power law form $\sim H^{-n}$. In the range 10^0–10^2 Oe, for the AH regime the n value is 0.38 and 0.39 for samples YBCO + 30CuO and YBCO + 15CuO, respectively. These values are close to those obtained by similar treatment of experimental $R(T)$ data [6–8] by AH model. For the flux creep regime, in the range 10^3–10^4 Oe, the n values are 0.2 and 0.25 for samples YBCO + 30CuO and YBCO + 15CuO respectively. The change of exponent n with increase of magnetic field observed in this work supports the conclusion that in the transition region 10^2–10^3 Oe, the crossover of dissipation mechanisms in Josephson network takes place.

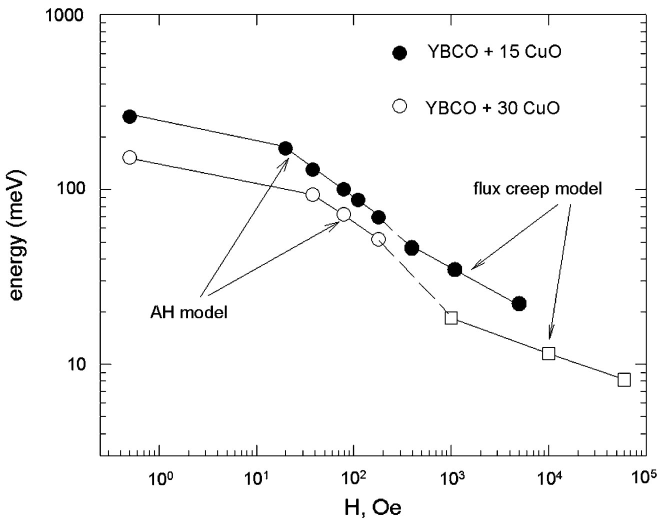

Fig. 4. Magnetic field dependences of effective Josephson coupling energy E_J obtained from best fits of $R(T)$ by AH model and effective pinning potential $U(H)$ deduced from slopes of Arrhenius plots of experimental $R(T)$.

4. Conclusions

We have studied the broadening of resistive transition of composites YBCO + CuO in magnetic fields up to 60 kOe. Analysis of experimental data have shown that the MR effect in low magnetic field (0–10^2 Oe) range is caused by phase slip processes in the network of Josephson junctions YBCO/CuO/YBCO realized in the composites. In the high magnetic field range 10^3–10^4 Oe, the dissipation in the Josephson media follows flux creep model with temperature independent pinning potential. There is a crossover in the intermediate field range 10^2–10^3 Oe from $R(T)$ behavior predicted by AH model to $R(T)$ typical for flux creep model.

References

[1] D.A. Balaev, K.A. Shaihutdinov, S.I. Popkov, D.M. Gokhfeld, M.I. Petrov, Supercond. Sci. Technol. 17 (2004) 175.
[2] M.A. Dubson, S.T. Herbet, J.J. Calabrese, D.C. Harris, B.R. Patton, J.C. Garland, Phys. Rev. Lett. 60 (1988) 1061.
[3] P.W. Anderson, Phys. Rev. Lett. 9 (1962) 309.
[4] V. Ambegaokar, B.I. Halperin, Phys. Rev. Lett. 22 (1969) 1364.
[5] M.I. Petrov, D.A. Balaev, K.A. Shaihutdinov, K.S. Aleksandrov, Supercond. Sci. Technol. 14 (2001) 798.
[6] A.C. Wright, K. Zhang, A. Erbil, Phys. Rev. B 44 (1991) 863.
[7] C. Gaffney, H. Petersen, R. Bednar, Phys. Rev. B 48 (1993) 3388.
[8] H.S. Gamchi, G.J. Russel, K.N.R. Taylor, Phys. Rev. B 50 (1994) 12950.
[9] A.V. Mitin, Physica C 235–240 (1994) 3311.
[10] M. Tinkham, C.J. Lobb, Solid State Physics: Advances in Research and Applications 42 (1989) 91.
[11] V. Ambegaokar, A. Baratoff, Phys. Rev. Lett. 10 (1963) 486;
V. Ambegaokar, A. Baratoff, Phys. Rev. Lett. 11 (1963) 104.
[12] J.D. Hettinger, A.G. Swanson, J.S. Brooks, Y.Z. Huang, L.Q. Chen, Zhong-Xian, Supercond. Sci. Technol. 1 (1989) 349.
[13] E. Babic, I. Kusevic, S.X. Dou, H.K. Liu, Q.Y. Hu, Phys. Rev. B 49 (1994) 15312.
[14] R.J. Soulen Jr., T.L. Francavilla, W.W. Fuller–Mora, M.M. Miller, Phys. Rev. B 50 (1994) 478.